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RESEARCH ARTICLE OPEN ACCESS

A PLC BASED CONTROL SYSTEM FOR LOAD FREQUENCY CONTROL IN AN ISOLATED SMALL HYDRO POWER PLANT

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ABSTRACT

Renewables provide 20 % of the power generation worldwide, being hydro power the cheapest and most sustainable way to generate power, representing almost a fifth of the generation worldwide. In Cuba, electrification in mountainous areas is through isolated small hydro power plants from the National Electroenergetic System. One of the most important components in hydro power plants is the frequency controller, due to the changing condition of the demand of power generated by users. The use of inefficient regulation systems with regulation techniques made from resistive load or ballast, provides the statement of frequency regulation through the management of the water flow as a viable technical solution. In the current work, the frequency regulation in the small hydro power plant "Hanabanilla" with a PID as a controller designed in Matlab Simulink and its implementation in a control system made from a PLC M241 by Schneider Electric is proposed.

I. INTRODUCTION

The generation of electric power through hydro power plants is one of the most efficient and safest ways to generate power. The beginning of its use dates back from the first Industrial Revolution in England, being the civil engineer John Smeaton its main promoter. Currently, it plays an essential role in the electrification of rural areas located far from the big networks of power distribution, especially in developing countries.

Normally, small hydro power plants, whose power ranges between 50 and 500 kW according to the Latin American Energy Organization (known in Spanish as OLADE) [1] are more profitable and cleaner for the environment than hydro power plants which have bigger power. There are two ways of operation in the small hydro power plants: isolated mode and that connected to an electric network. By working in both ways of operation, consumers require a continuous and quality service, being the frequency of the system one of the quality rates. Deviation of the instant frequency value is an inevitable fact due to the imbalance produced between generation and the charges connected to the system that vary randomly depending on the incorporation or desconnection of such charges. In order to maintain the instant frequency value of the system within the recommended ranges, it is necessary to implement a frequency regulation mechanism.

The problem of frequency control in small hydro power plants can be pictured as a rejection before disruption [2] and it is subject to variations of operation's conditions of the plant. The load-frequency control or automatic control of generation (known in Spanish as AGC) is focused on maintaining the frequency within the permissible limits and controlling the interchange of power between the different areas. In Cuba, out of the 107 small and micro hydro power plants currently working, only six of them have some frequency regulation mechanism, and since these systems are technologically obsolete and energetically inefficient due to the use of the load or regulation for ballast resistances, it is necessary the design of a frequency control in isolated systems which are adapted to the demands of quality in the generation of electric power and which are best used on the available water resource.

The small hydro power plant "Hanabanilla" ranks in the type of run-to-the-river small hydro power plant and consists of a unit which generates 130 Kw of power with a Pelton turbine, and it is currently working connected to the National Electroenergetic System (known in Spanish as SEN), since it does not possess a frequency regulation system to work in an isolated mode. Since its beginnings, this small hydro power plant worked in an isolated mode with an electronic system of frequency regulation by resistive load, being its purpose to feed the plant service of the Hydro power Plant "Hanabanilla" with 43MWh and the Administrative Building of the entity. This regulation system broke down leaving the unity inoperative until it was decided to syncronize it to the National Electroenergetic System (known in Spanish as SEN).

The proposal to design a frequency regulation system for the small hydro power plant intends to get the unity which generates back to work in isolated operation, as it was originally conceived, working as a backup to the plant service of the Hydro power Plant "Hanabanilla" before eventualities such as cyclones or breakdowns in the Hanabanilla-La Moza-Santa Clara System, so as to perform a black start without having to depend on the SEN.

The main contribution of this work is the proposal of a frequency regulation system made from PLC in a small hydro power plant where the final action element is a servomotor which is controlled by a Lexium 32 servo control.

II. THEORETICAL REFERENCE

Two main ways to control the frequency in small hydro power plants are known: the control of the water flow which gets in the turbine and the adjustment of the generator load by using resistances banks for the adjustment of the frequency [3], though Peña's work [4] successfully combines both regulation methods so as to reach an optimus adjustment of the frequency-load control as the operation point of the plant varies. The first method consists of adjusting the controller to an operation point of the plant by regulating the quantity of water that flows into the turbine [5] and the second fixes the operation to a value of constant power, normally the maximum value, by balancing the loads of the users with a resistive loads system connected in parallel [6],[7].

From these two main ways to operate an isolated small hydro power unit, a wide variety of control methods in the scientific litterature has been implemented in order to solve the problem with the frequency regulation in this type of systems. Some of the most well-known methods are the Fuzzy Multimodel Control [8], the Intelligent Hybrid Control [9], the Multiple Flow Control [10], the Integral Control based on Neural Networks [11] and the Adaptive Control [12], [13]. A review [14] did some research on the new operation strategies and control for electric distribution networks connected to small hydro power plants.

A scheme of Sliding Mode and model order reduction has been recently implemented by Qian [15] for the solution of the problem concerning frequency-load control in small hydro power plants. In this project, how the system in the two ways of operation works is explained: isolated and connected to an electrical network. The system is modelled mathematically under both ways of operation, by obtaining the reduced model for its further analysis and, according to the order reduction model, a sliding control algorithm is applied. Since the control algorithm is applied to the original system, a sufficient condition about the stability of the system according to the theory of small earn in control systems is demostrated.

A combination of the diffuse logic and the adaptive control comes true in Weldcherkos's proposal [16], where he uses an adaptive inference system with diffuse logic (Adaptative Neuro-Fuzzy Inference System - ANFIS) and this result is compared with the responses of the system with a conventional PID control. By using ANFIS, a faster transitional response is achieved (5-second order), much more than using PID (60 seconds).

An adaptive controller with diffuse logic for small hydroelectric plants by Özbay and Gençoğlu is proposed [13], by using dynamic models of linear and non-linear turbine without taking into account the water hammer effect. It is interesting how faster settling times are achieved with the non-linear model than with the linear model by using this algorithm.

On the other hand, Asoh, Mbinkar, and Moutlen [17] propose a PI control with diffuse logic in a linear plant model and in another case with non-linear model. The obtained results in the simulations for the linear plant showed settling times of 95 seconds with a conventional PI, while with a PI control with diffuse logic the settling times were of 12 seconds, this with load variations of a 3% of the total value of the plant generation power.

A controller of variable structure is introduced by Kumar and Mathew [18] to show the significant improvement in the transient response with different step-typed reference inputs for changing loads. The authors explain the functioning of a plant working in isolated mode and the range of power losses. They also reduce the value of wasted power to a 50% of the power delivered by the plant, due to the variation in the water flow.

Another of the tendencies is the use of an electronic load controller, developped by Kapoor, Phunchok, Kumar and Rahi [19], which senses and regulates the frequency generated by a small hydro power plant. It is explained in the work that an electronic load controller is a solid state device, designed to regulate the output power of a small hydro power-typed generation system and keep to the closest possible constant load value in the turbine to generate stable voltage and frequency.

Kenzhaev [20] proposes the use of an automatic digital microprocessor control system, based on the analysis of the current use of digital frequency controllers as automatic ballast load controllers for small hydro power plants. At present, there are two practical circuit designs of this type of a controller: 1. Step ballast load connection to the generator output using a contactor-relay switching; and 2. The use of analog power semiconductor automation (analog ballast load). The advantage of this solution is more accurate automatic control. One of the most promising circuit designs for small hydro power plant ballast load controllers is a digital frequency controller. Digital measurement is widely used in modern circuitry, characterized by high accuracy and is well combined with a stepwise automatic ballast switched by thyristor contactors. The practice of using digital frequency controllers to stabilize the rotational speed of an off-grid small hydro power plant has shown that they provide adequate power plant dynamic indicators and stable plant operation with almost all types of hydraulic turbines.

While Marques and Molina [21] discuss in a detailed way the modelling and the proposal of a new control scheme of a three-phase electrical network connected to a small hydro power type of plant. They implement a new control scheme, which consists of a multi-level hierarchical structure and it adds a maximum power point tracker for a better use of the hydraulic power contributed to the system.

Karthikeyan, Menna Eligo and Dawit [22] also propose a control structure with a tuning method for a load-frequency controller in systems of PID type of power. The proposed scheme assures stability in the system during dynamic state conditions.

Saad's work [23] is based on the design of a PID control for an isolated small hydro power plant. The simulations of the plant with the PID varying the operation point of this, result in settling times between 9 and 30 seconds for a variation of the load by disturb of 2% out of the total of the installed power.

A Digital PI control algorithm is proposed by Huerta [24] for the speed regulation in a synchronous Pelton-generator turbine system in a small hydro power plant. The developped scheme is waterfall-type with a proportional control in the internal bow and an integral-proportional control in the external bow, achieving a settling time response of 12 seconds before a unitary step input.

Peña, Fariñas and Domínguez [4] bring forward a proposal for the adjustment of a controller by looking for the optimum operation point of a small hydro power plant through the combination of both ways to regulate frequency: by resistive loads (ballast) and through the water flow control which goes into the turbine. Settling times up to 5 seconds for impulsive loads of 11% are obtained and in the range between 20 to 30 seconds for step type of input of 13%.

In Shashikant and Shaw's research [25], an interesting comparison as for the tuning of the PID type of control is made by using three different optimization methods: Lightning Search Algorithm (LSA), Particle Swarm Optimization (PSO) y Quasi Oppositional Based Lightning Search Algorithm (QOLSA). Finally, the optimized PID with the QOLSA method showed better voltage and power responses to the output of the unit than that with the other methods.

A PI controller has been used by Safaei [26] to reduce the peak of frequency deviation. The optimal gain of PI controller and integrator of dump load is obtained by genetic algorithm (GA) to achieve minimum frequency deviation. In this method, the peak of frequency deviation is reduced less than 1 Hz while in the conventional scheme, the peak of frequency deviation is 3 Hz. In other words, the positive or negative peak of frequency deviation has been reduced about 60%.

Gupta [27] proposed in his work the use of a Programmable Logic Controller (PLC) for control and automation of small hydro power (SHP) station, its advantages and cost effectiveness. Programmable logic controllers (PLC) can be used for control & automation of SHP station. The main reason for this is cost effectiveness. Various functions and controls can be achieved by programming the PLC. They can be used for full plant automation including governing of auto-operation includes speed control, load control, excitation control, and level control automatic start/stop sequencing, gate control, start/stop of auxiliary systems, and protection requirement etc. Functions other than control like continuous monitoring, data recording, instrumentation and protections can also be performed. For remote operation, communication with PLC can be performed. For continuous monitoring purpose, a personal computer can be interfaced with PLC and continuous data can be recorded regularly.

Alam and Chopra [28] paper present a project based on Proportional–Integral–Derivative (PID) for the implementation of load controller for three-phase synchronous generator. Electronic load controller is a device which is related to power electronics method of controlling, managing and monitoring frequency of a system. Mostly, in rural areas, we do not have access to grid for power. There pico- and micro-hydropower can be implemented to provide power. For persistent operation and control of a three-phase synchronous generator, an electronic load controller has been implemented rather than using speed controller governor which is much more expensive. With the help of the proposed device, load output can be controlled, and thus, frequency can be maintained constant which again reduces worst case of overloading on generator. Therefore, with the help of the proposed scheme, protection of both generator and user's load can be maintained. The proposed system can play a vital role in run-off-river type hydropower station because there is no point of saving water. Thus, the proposed system can be used to minimize the overall cost of installation of the hydropower plant up to a large extent in rural areas where we do not have access to grid connection for electricity.

Maina [29] paper investigates the performance of a single unit small hydropower plant in both grid-connected and islanded operation. The overexcitation and volt/hertz excitation limiters have been included in the study to compare their responses in both modes of operation. The plant is evaluated under different loading scenarios considering both resistive and inductive loads. A PI tertiary control for speed reference setting in islanded operation is introduced in the governor to enable regaining of 50 Hz frequency after load changes. The results obtained from the simulation study show the importance and difference of analysing different loading scenarios both in grid-connected and island modes. Also, the inclusion of PI control in governor aids in returning the frequency to its nominal value.

III. MATERIALS AND METHODS

The modelling of the turbine-generator system of the small hydro power plant "Hanabanilla" was performed by having into account the technical data of the plant and taking as reference the linear model stated by Kundur [30], where it is assumed that:

- The water resistance is significant.
- The water pipe is inelastic and the flow is incompressible.
- The water flow speed varies directly with the sluicegate's opening and with the square root of the net hydraulic load.
- The output of the unit's power is directly porportional to the product of the hydraulic load and volumetric water flow.

For the Pelton turbine model, 100 meters was taken as an average hydraulic load and an average water speed in the pipe of 6.5 m/2, staying as transferential function of the turbine:

$$G_t = \frac{-4s+1}{2s+1} \tag{1}$$

While for the 200 kW synchronic generator, from the electrical data, the load-damping constant was calculated D=0.8 to find the $Kp = \frac{1}{\frac{\partial Pl}{\partial F}} = \frac{1}{D}$ of the generator and the time constant $Tp = \frac{2*2.88}{60*0.8} = 0.12\ s$, resulting in:

$$G_p = \frac{1.25}{0.12s+1} \tag{2}$$

As an element of final action a direct current servomotor fulfilling with high dynamic performances and being capable of developing a constant nominal torque of 33 Nm was chosen, given by the mechanical demands of the injector needles of the turbine. It is well-known that this type of drive gives stability to the system for being a first typical order, this in detriment of other electro-hydraulic type of actuators that are also mentioned in litterature [30], [31], but that present non-linear features in its behavior.

The transferential function which describes the dynamics of the direct current selected servomotor is given by [32]:

$$G_k = \frac{10}{0.0139s+1} \tag{3}$$

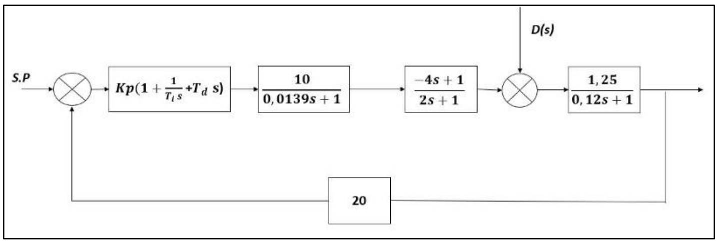

Figure 1: Control scheme of the small hydro power plant "Hanabanilla".
Source: Authors, (2022).

The droop constant of the system was taken into account R=5%, thus, we have in the feeback 1/R=20, as it is stated by Kundur [30].

Due to the need of achieving a response from the system with zero error in stable state so as to achieve to keep the frequency in 60.00 Hz, it was decided to firstly tune a PI type of control before the value-step entry 30 for disturb, by making use of the Matlab-Simulink software and to assess its performance. The transitional response with the comprehensive proportional control, with Kp=0.015 and Ti=0.5s, is considered to be quick, with settling time of 7.3 seconds; however, it was decided to tune a PID control so as to improve the transitional response.

The tuned PID shows a response with settling times of 6.6 seconds, having as the following parameters: Kp= 0.016, Ti= 0.5 s, Td= 0.1 s.

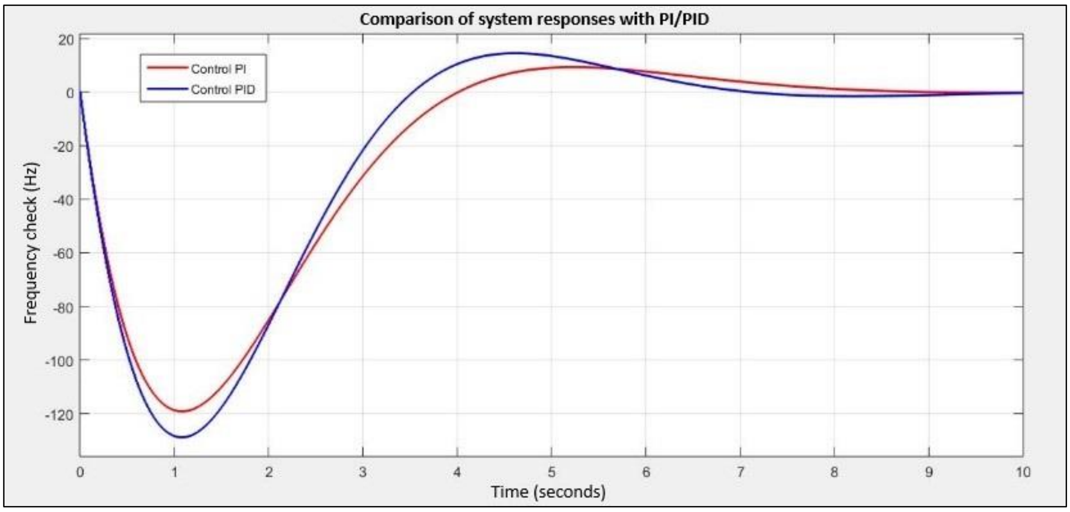

Figure 2: Variation of the frequency with controllers type PI and PID.
Source: Authors, (2022).

In the figure 2, the improvement of the response of the PID respect to a PI type of control is showed. In red color, the response of the PI and in blue, that of the PID. The improvement of the transitional response which introduces the derivative action in the PID, makes this to be the chosen one in detriment of the PI. It is evident the inverse response of the system given by the zero in 0.5 which introduces the transferential function of the hydraulic turbine, which brings stability problems and a slow response given that two physical phenomena with opposed dynamics are manifested in the process.

The frequency regulation proposal in the small hydro power plant "Hanabanilla" is based on a Control System made from PLC M241 by Electric Schneider. The reason for his choice is given by the robustness and demonstrated reliability which provide the control systems made from programmable logic controller (known in Spanish as PLC) and its high flexibility in the configuration of the software and the hardware, as well as the capacity they have to execute several tasks and operations in real time simultaneously.

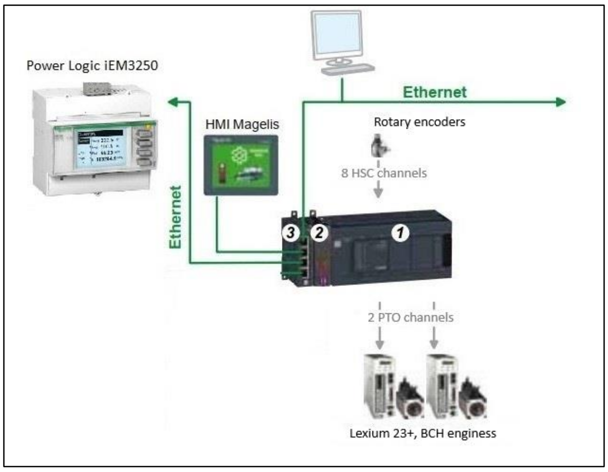

Figure 3: Control paltform based on PLC M241.
Source: Authors, (2022).

M241 has two Pulse Train Output (PTO), which will be necessary for the control of the position of the two CD servomotors, which will work on the needles of the injectors of the turbine through the Lexium 32 servo controllers (*servo drive*) of the own Schneider Electric manufacturer.

It is also fundamental the possibility of setting a PID function within the M241 programming logic, allowing to put into practice the design of a controller of this sort.

Automaton programming was performed with the software created by the own SoMachine v.4.3 manufacturer. Aside from tuning the PID controller, the electrical drive of the CD servomotors with the Lexium 32 module was set in the program, and all the boot sequence, the stop and the unit operation, as well as the alarms and plant's shots were programmed.

The design of the control system was performed by taking into account that the turbine has two injectors, therefore, it is necessary to use two servomotors for its drive. Schneider Electric M421 PLC only has two Pulse Train Output (PTO). When combined with the Lexium 32 servo drive, they only allow to control only one servo since it is necessary to change the direction of rotation of both motors to achieve the opening and closing operations of the injectors. It was then decided to control the first one with PID through the two Pulse Train Outputs for a fine adjustment of the system frequency and the other servomotor was controlled with a ON/OFF controller.

A Power Logic iEM3250 network analyzer is used as an element of the frequency measurement so as to communicate with the automaton by Modbus Serial IOScanner protocol and transfer the reading value of the system frequency, as well as the other electrical parameters such as active and reactive energy, power factor, voltages and phases currents for the setting of the alarms and plant's shots.

Figure 4 shows the frequency control loop according to the ISA S5.1-84 norm: the Lexium 32 (FC-2) servo controller and the Schneider Electric M241 PLC (PLC-1) constitute the controller, the servomotor of direct current (FZ-2) is the actuator, and the Power Logic iEM3250 network analyzer (ST-2) is the measurement element closing the control loop.

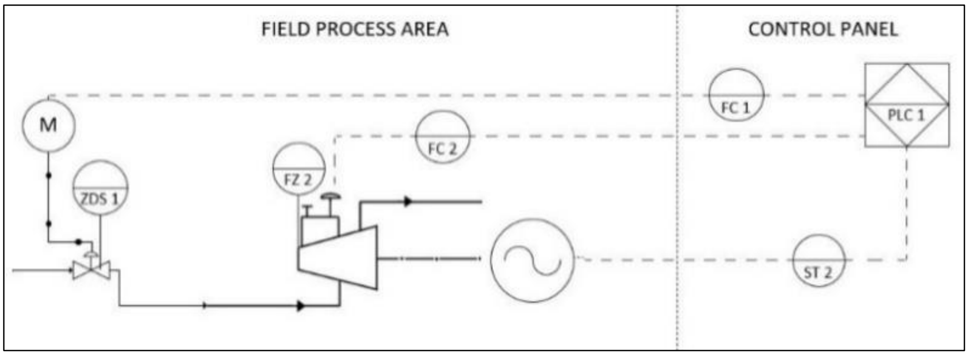

Figure 4: Frequency control loop scheme according to the ISA Norm.
Source: Authors, (2022).

The scheme also includes the motorized valve control which allows the water input to the turbine, which is operated with a frequency converter (FC-1) located in the control panel. This is an ON/OFF type of control and is covered by the boot sequence and stop of the plan.

IV. RESULTS AND DISCUSSIONS

The effect of varying the operation point of the plant (hydraulic load) with the PID controller in the control system of the Small Hydro power Plant "Hanabanilla" does not damage significantly the system response. Figure 5 and Table 1 reflect the behavior of the system response in each case.

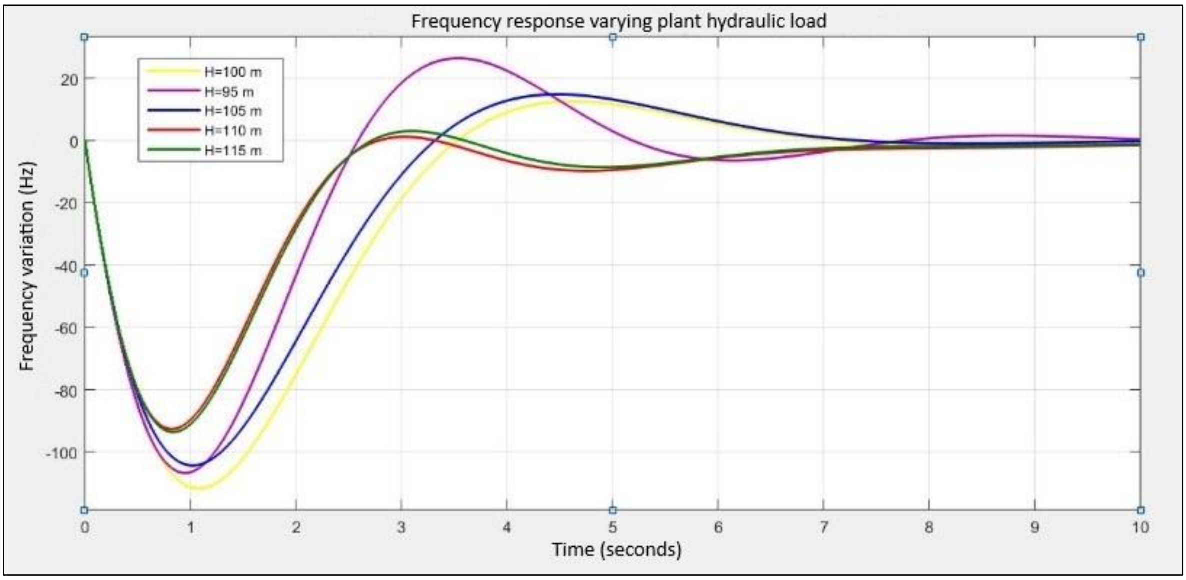

Figure 5: Variation of the plant response with the PID varying the hydraulic load.
Source: Authors, (2022).

As showed in the graphic of figure 5, settling times in the most critical cases never exceed the 10 seconds time despite the variation of the operation point of the plant with the change of the hydraulic load of the unit. Similar responses were obtained in the works presented by Padhan and Majhi [33], Tan [34] and Anwar and Pan [35], where from the PID controllers designed by frequency method [33], [35], and from IMC inner controller model, settling times of 4.4 seconds and 8.4 seconds respectively were obtained.

Table 1: System response with PID varying the hydraulic load.

Hidraulic load	Response	Maximum overshoot %Mp	Settling time-ts
95 m	Violet	32	9.5 seg
100 m	Yellow	16	6.6 seg
105 m	Blue	18	6.9 seg
110 m	Red	3	7.3 seg
115 m	Green	5	7.5 seg

Source: Authors, (2022).

A PID controller for the load-frequency control in a plant with similar features to that of the present article is tuned in the work of Saad and Chi [23]. For a turbine with response time of 4 seconds and with a droop feature of 5%, the tuned controller by Saad grants the turbine-generator system a much slower response (33.6 seconds) that those obtained in this work. The simulations performed by Saad were for variations of the demand of 2% of the total generation capacity of the generator whereas those performed in this work were of 25%. Once the adjustment of the PID control was obtained through the stated technical design requirements, all the control logic of the small hydro power plant “Hanabanilla” was programmed. The boot sequences and stop of the unit, the process and safety interlocks, the alarms and the shots of the plants were taken into account. The reading of all the electrical parameters of the generator, sensed by the Power Logic iEM3250 network analyzer, lead to the supervision and control of the plant’s shots and to a safe operation.

The functioning of the program with the the same simulator of the SoMachine v4.3 software was simulated, by forcing all the conditions so as to check the correct functioning of the sequences automatically from the PLC.

The setting of the Lexium 32 servo drive was done through the features and dimensions of the Pelton turbine that the plant has and the servomotor of the direct current selected for the drive of the injector needles. The alarms and servo stops were taken into account to include it in the automaton logic.

V. CONCLUSIONS

The design of a PID controller, through the linear model of the plant is adjusted to the technical operation demands of a isolated small hydro power plant and the settling times of the response before variation of the hydraulic load are similar to those stated in litterature.

The choice for a direct current servomotor as an actuator element in the control loop gives stability to the system.

The use of the PLC M241-based control platform by Schneider Electric allows a flexibility both in the development of the control system and in the communication of this with supervision systems that can be added in higher levels of the automatization pyramid.

The use of the Lexium 32 servo controller integrated to the PLC-bsed control platform for the frequency regulation in a small hydro power plant constitutes a contribution to this work so as to give a technical solution to the state problematic, since this type of servo actioning are frequently used in applications of packing and packaging lines processes in the food-processing industry where the speed control of conveyor belt and the position control in different axes is necessary, given that the use in the control areas of the electrical power systems is not well stated in litterature.

VI. AUTHOR’S CONTRIBUTION

Conceptualization: Ing. Julio César Bravo Cortés, Dr. H.C. José Rafael Abreu García.
Methodology: Dr. H.C. José Rafael Abreu García.
Investigation: Ing. Julio César Bravo Cortés.
Discussion of results: Dr. H.C. José Rafael Abreu García.
Writing – Original Draft: Ing. Julio César Bravo Cortés.
Writing – Review and Editing: Ing. Julio César Bravo Cortés, Dr. H.C. José Rafael Abreu García.
Supervision: Dr. H.C. José Rafael Abreu García.
Approval of the final text: Dr. H.C. José Rafael Abreu García.

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